Matrix analysis: A technique to investigate the spatial properties of handwritten images

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Abstract: *Research on objective measurement strategies to assist forensic handwriting experts to make judgements about spatial consistency are providing novel techniques that exhibit considerable potential. We have developed the 'Matrix Analysis' computer program based on the PEAT system philosophy that allows the operator to objectively select measurement points from handwriting, edit these points according to the accepted relationship between curvature maxima and velocity minima, and calculate automatically the measurement range between all the combinations of points selected. This provides the examiner with a semi-automated objective score of the spatial consistency of the questioned image when compared to the range of variation in the standard images. On a typical signature the Matrix Analysis technique compares between 25,000 and 100,000 measurements to generate a spatial consistency score. It is at the stage of determining whether a questioned image is consistent or inconsistent with the range of variation in a standard image group that techniques of this type offer great potential. Examiners of handwriting can then use this information to explore hypotheses from which opinions regarding authorship can be mounted.*

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1. Introduction

A fundamental of forensic handwriting theory relates to the difficulty which individuals experience when attempting to copy the handwriting traces produced by others. The simulator is required to produce what are often a complex series of movements with the aim of generating an image that captures the appropriate combination of space, construction and line quality characteristics. The approach to the investigation of this phenomena in the forensic environment has centered around literature and personal experiences of attempts to simulate writings (Osborn, 1929; Harrison, 1958; Conway, 1959; Hilton, 1982; Ellen, 1989). Much of this information and research has necessarily relied on purely subjective comparison processes. The almost total absence of objective measurement approaches in forensics can be attributed to a number of factors, the most significant being the difficulty in taking and comparing measurements from images that are directional, non-linear and where one portion of the line may intersect and overlap with previously formed sections. An example of such a signature is shown in Figure 5. In addition, the objective assessment of line quality, a measure of fluency or dysfluency of movement, is difficult to achieve on static images. Compounding the philosophy of the importance of objectivity in comparisons is that the data generated does not necessarily provide the examiner with information that may be relevant to issues of authorship. Found and Rogers (1998) have argued that objective tests of

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the type discussed in this paper are important in the first phase of opinion formation. The primary opinion at this stage concerns whether or not the examiner believes that a questioned image is consistent with the known image in terms of line quality, construction and features associated with space. Computer techniques clearly can provide detailed information regarding spatial consistency which would be difficult to extract using visual processes. According to the traditional texts, observational approaches have been shown to be both efficient and effective. The difficulty with these types of approaches, however, is that visual information may be treated differently, depending on the observer. In an expert system the opinions of one expert may be contrary to the opinions of another, and this has clear implications for the social justice system. Without objective techniques or indices, it may be extremely difficult to isolate the basis of the difference in opinion.

Computer-based handwriting analysis systems are being reported from a variety of fields including handwriting recognition, signature verification, signature identification, database searching, forensic comparison and administrative areas. Signature identification systems aim to identify a questioned signature from a database of known signatures. Han and Sethi (1996) described a signature identification system that utilised geometric (horizontal and vertical bars, loops etc.) and topological features (end points, branch points etc.). The extracted comparison features were then normalized to control for translation, rotation and scaling. A number of search and match strategies were then applied to attempt to optimize the identification of the questioned signature from the reference set. Murshed, Bortolozzi & Sabourin (1996) described an off-line signature verification system which, it was argued, compared images in a similar way to forensic experts. The technique involved preparing the image to remove background information, dividing the image into a number of smaller regions and comparing features within each of the regions to regions within images in the database. A decision is then made regarding the identity of the signature based on a training technique with genuine signatures. Although there is great potential to apply such techniques in the forensic environment, there are some limitations that must be noted. Forensics necessarily deal exclusively with static signatures so verification based on dynamic data, even though some of this data can be inferred (Found, Rogers & Schmittat, 1997), cannot be utilized. The validity of applying algorithms that normalize or distort the image may be a cause for concern in the court environment where such changes made to images extracted directly from items of evidence is subject to criticism. Off-line systems still do not appear to be extracting line fluency information.

Research on objective measurement strategies which may assist forensic handwriting experts to make judgements about spatial consistency are providing novel techniques that exhibit considerable potential. Phillipp (1996) provides a summary of some of the systems which are more relevant to forensic handwriting examination with a view to assessing their applicability as a supplement to existing subjective comparison approaches. These systems have shown to be capable of detecting 100% of random and simple forgeries and over 90% of skilled forgeries (Ammar, 1995). The 'Forensic Information System for Handwriting (FISH)' is a well known system within the forensic sciences and uses a combination of manually entered descriptive features, automatically calculated non-textual features, textual features and features which are measured with the assistance of the operator, to define a sample of questioned handwriting and compare it to a large number of both known and unknown writing samples in a database (Hecker, 1996; Philipp, M, 1992). Sagar and Leedam (1996) noted the limited research effort in the field of forensic document examination with regard to automating the comparison process. These authors describe a number of collaborative projects dealing with computer-aided examinations. The Forensic Document Examination System (FODES) is a software package that enables the examiner to extract characters from digital images and generate charts using these characters and overlay images. It has been reported that this technique provides a significant time saving in the routine construction of display charts (Holcombe, Leedham & Sagar, 1996). The Writer Identification System (WIS) combines information extracted from the context of the document content in combination with global features (character slant, size, ascender and descender heights etc.), interactive determined

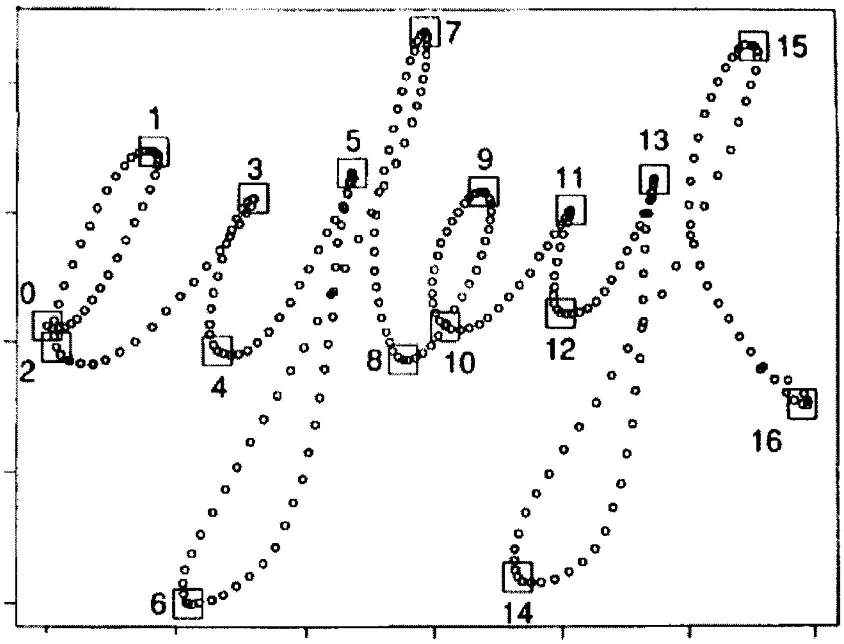


FIGURE I. A sample of handwriting with marks indicating stroke based segmentation. Each dot in the trajectory represents a sample equally based in time. The tangential velocity of the pen along the curve is proportional to the radius of the curve at any point. (Wright, 1993, *Acta Psychologica*, 82, 5-52.)

local features (character classifications according to temporal construction) and texture features which can be generally thought of as characteristics of the image independent of their linguistic meaning. This information is planned for use in the comparison process but is reported to still be in its research phase. The *Forensic Document Examination Tools* software is reported to be a similar system to WIS but is designed to extract global and local features automatically. This system is also reported to still be in its development phase.

The Pattern Evidence Analysis Toolbox (PEAT) (Found, Rogers & Schmittat, 1994) and the related Angular Differential software (Found, Rogers & Schmittat, 1997) were developed along a similar philosophy to those systems described above. The approach adopted for our systems was based on overcoming the traditional measurement difficulties by designing specific tools to follow the path of the line (Smartline), interact with the operator (PIG Grid) and rationalize spatial measurement points according to motor control theory and the observation that maxima in line curvature correspond to velocity minima. Evidence of this is provided in Figure 1. The systems developed by the authors are specific to the comparison of like images; that is, comparing a questioned signature to a group of known signatures with a similar identity to derive a measure of the consistency of the questioned image in terms of space. The approach rationalizes the comparison using the relationship between the dynamics of signature production and extractable measurement points from the static image. Once the temporal sequence of the measurement points is determined, the spatial characteristics of the signature image can be thought of as a series of temporally ordered points in space. These points are therefore analyzed and are thought to represent all of the characteristics that document examiners subjectively assess in terms of spatial features (eg. ascender and descender heights, internal proportions, etc).

An obvious criticism that can be levelled at objective measurement techniques is the choice of what is to be measured on a particular image in combination with questions as to what is to be done with the measured data. Techniques such as the PEAT and other measurement strategies can, to different extents, be susceptible to criticisms on these grounds. The *matrix analysis* technique described here overcomes criticisms of this type as the operator is provided with a method of objectively picking the measurement points, using the angular

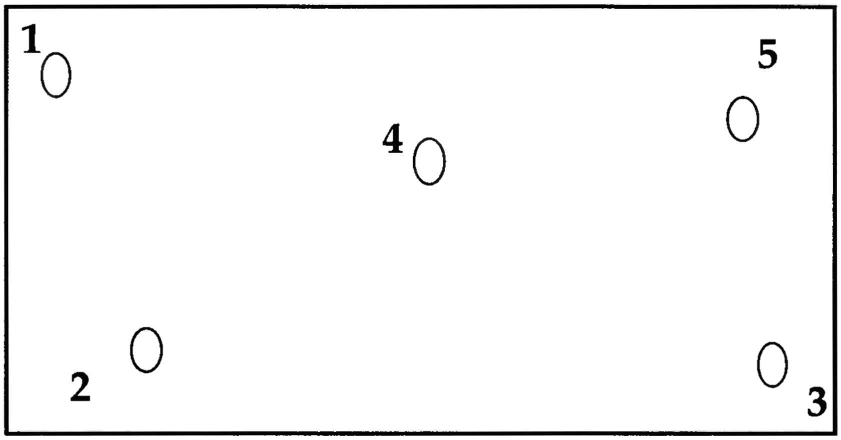


FIGURE 2. Points of velocity minima, corresponding to curvature maxima, isolated from a static signature. It is the relative position of each of these points that is determined using the matrix analysis program.

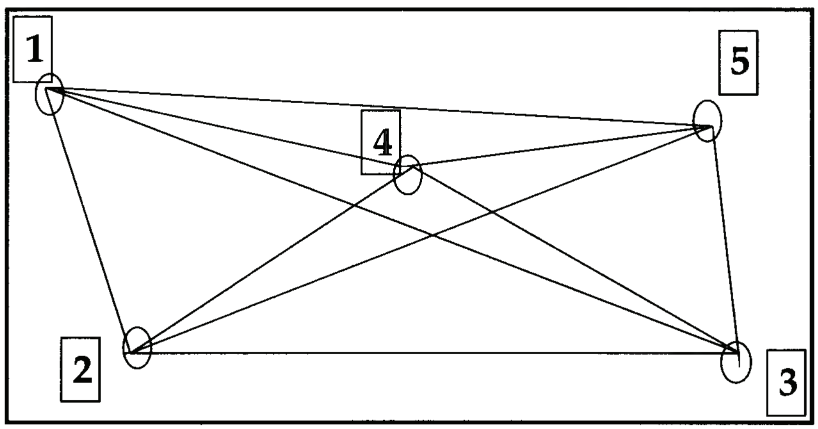


FIGURE 3. Raw distance measures calculated by the matrix analysis program eg. measurement in millimeters of 1-2, 1-3, 1-4, 1-5, 2-3, 2-4 etc. From this data the ratio of distance measurements are determined eg. 1-2/1-3, 1-2/1-4 etc.

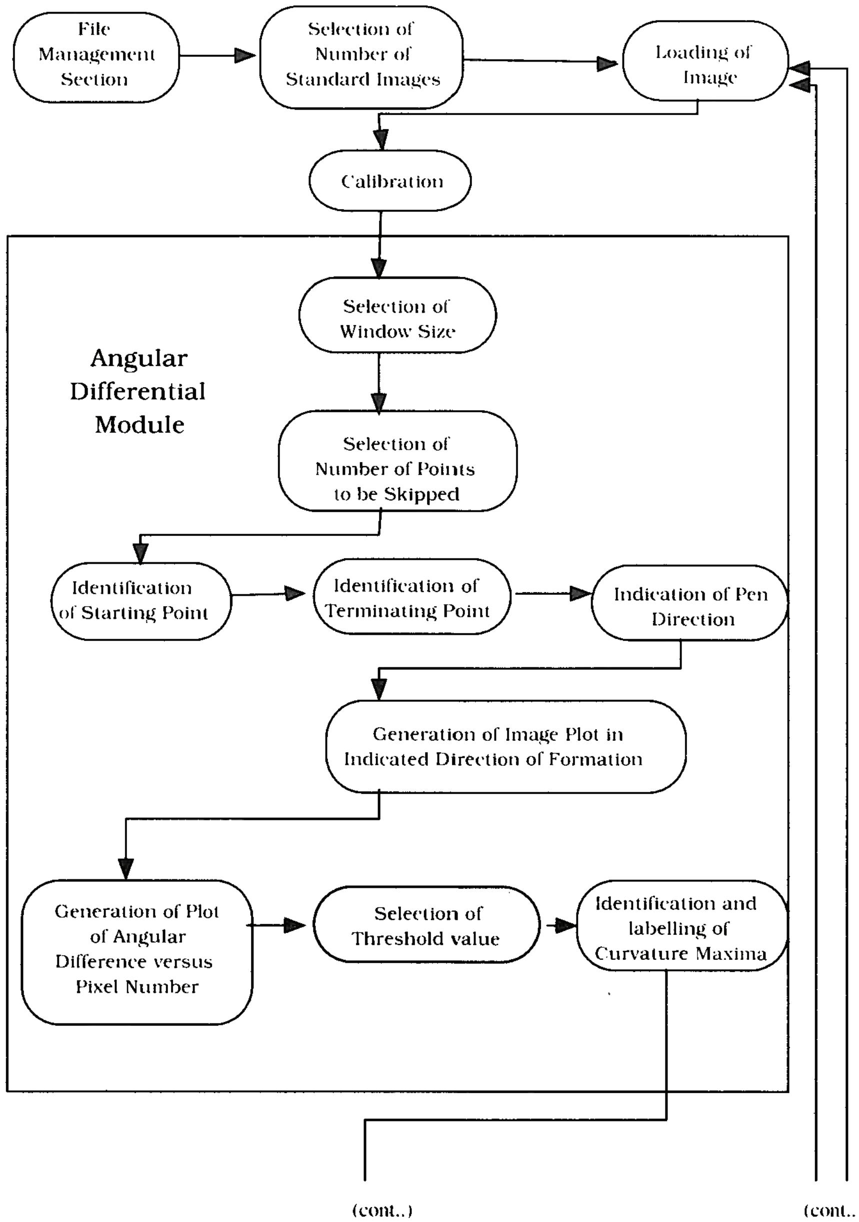
differential module, and measuring the distances and the relationship between the distance between all the measurement points identified. In this way a total spatial consistency score can be measured for each of the questioned images and compared to the standard image group.

2. Equipment

This technique requires a Macintosh series II computer or above, a scanner, the *Matrix Analysis* software, an image processing package (NIH Image 1.41-1.57) and a spreadsheet package (ClarisWorks).

3. Method

The basic technique is to scan both the questioned and standard signatures into the computer. These images are then reduced to a line thickness of one pixel using a skeletonisation technique such as that provided within the NIH image software. Images are then sequentially opened into the *Matrix Analysis* software where the points of maxima curvature are identified with the assistance of the Angular Differential software. Once the measurement points are identified and their temporal order entered, the software calculates all combinations of distance



measurements between the points and compares the range of variation in these measures in the standard material with the corresponding measurements in the questioned material. A spatial consistency score is calculated and provided to the examiner in spreadsheet form. In simplified format Figure 2 represents an array of temporally ordered velocity minima points associated with calculated curvature maxima after the line trace itself has been removed. Figures 3 and 4 show the matrix measurement strategy employed to generate a final spatial score. It is the values of each of these measurements calculated from the questioned signature that is compared to the range of variation in the values of the same measures in the standard group that is used to generate a spatial consistency score. The details of each of the techniques are given below and are represented in summary form in Figure 4.

4. Image Preparation

Since handwritten images are relatively small it may be necessary to enlarge them before the scanning process. This can be achieved using an enlarging photocopier. Images requiring analysis are enlarged

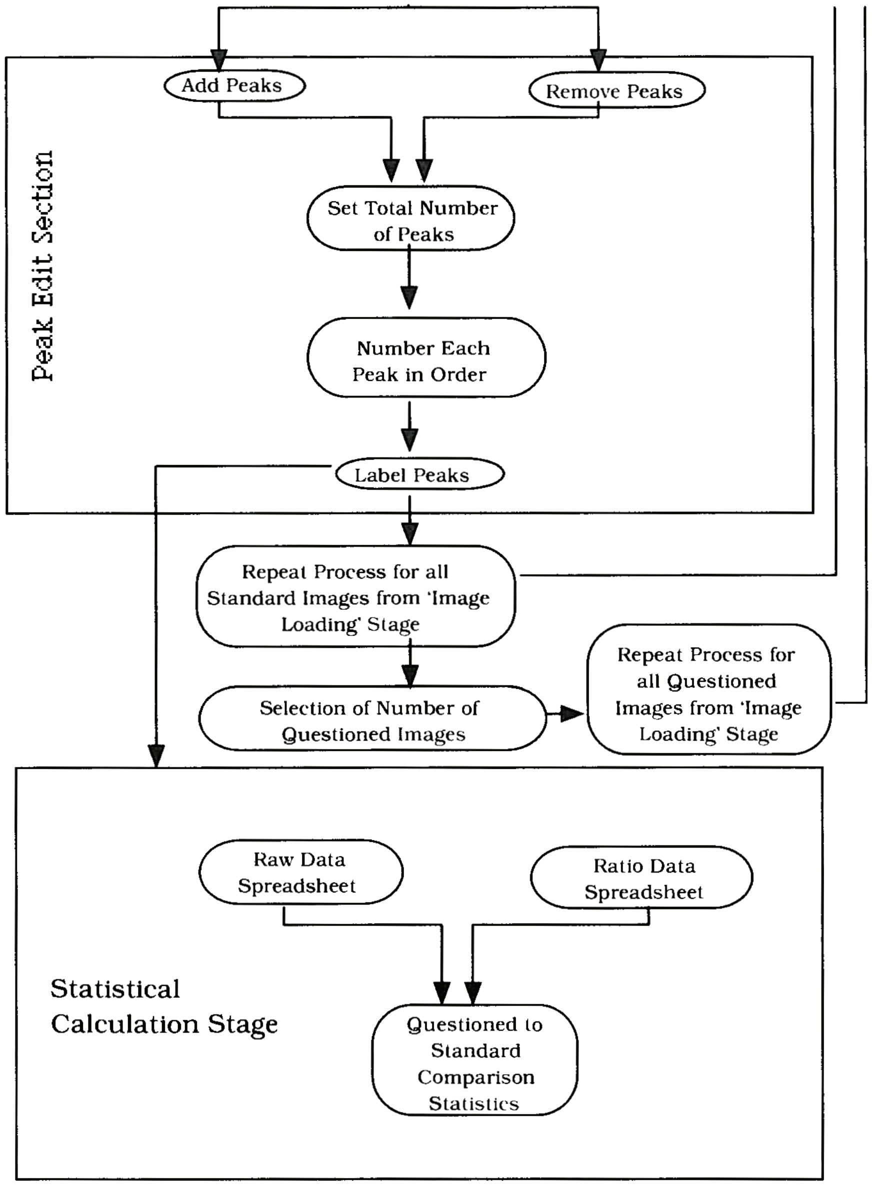


FIGURE 4. An overview of the Matrix Analysis technique for objectively comparing the spatial consistency of a questioned image in comparison to the range of variation in a standard im

to approximately fit across an A4 sheet of paper. A calibration grid accompanies each image through the enlargement process.

5. Scanning

The enlarged images are scanned into the computer and saved as a PICT file. Once all images have been scanned they are processed using NIH Image software.

6. Image Processing

A routine such as density slicing is carried out on the image to set the upper and lower grey scale limits that will res.ult in the image appearing as a complete and continuous line. Under normal circumstances a simple threshold routine will accomplish this. Images are converted to a binary form by setting the image pixels to black and all other pixels to white. A skeletonisation routine is applied which reduces the lines in the image to a thickness of one pixel. The processed images are saved in a MacPaint format (72 dpi).

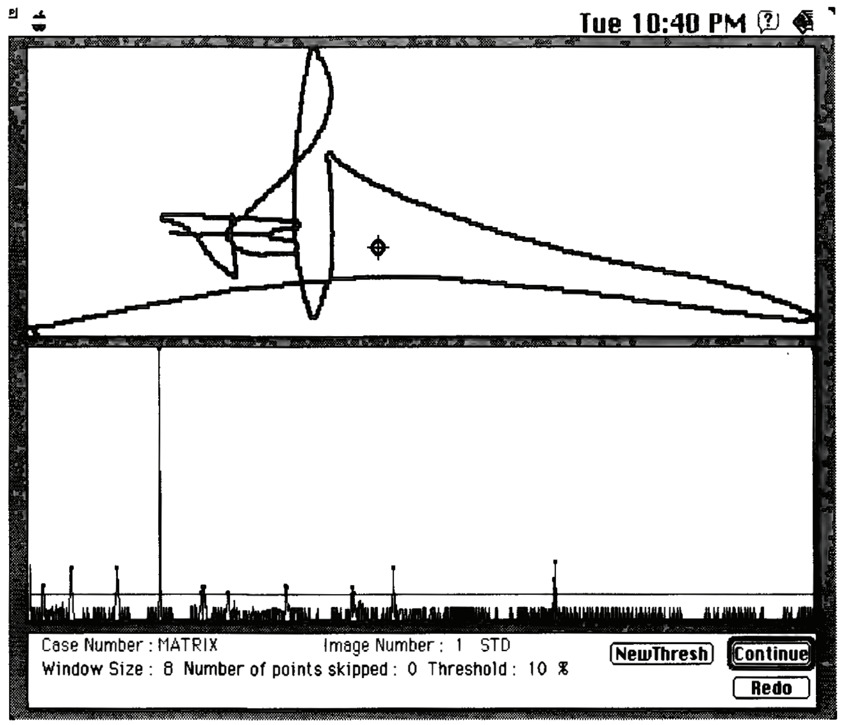


FIGURE 5. The Angular Differential results screen.

7. The *Matrix Analysis* Technique

The *Matrix Analysis* Technique is a stand alone module that utilizes the PEAT file management, calibration and Angular Differential software (Found, Rogers & Schmittat, 1994; Found, Rogers & Schmittat, 1997). Once the image has been opened into the Matrix package, the operator is prompted to enter information regarding the location of the starting point, the terminating point and pen direction for each line segment in the image. From this information the Angular Differential result screen is generated.

Figure 5 displays a result screen of the Angular Differential module (Found, Rogers, Schmittat & Metz, 1995; Found, Rogers & Schmittat, 1997). This technique identifies curvature maxima in the line. The screen is divided into three windows. The uppermost screen is a reproduction of the image being analyzed. The cross-hairs represent the average x and y values of the signature image pixels, where intersections and retraced portions of the line have been appropriately measured. The middle window is a plot of angular difference versus pixel number. The horizontal line represents the threshold value entered by the operator. The peaks above this line are colored. The corresponding pixel in the image window is also colored for identification. It is these colored pixels that are used for *matrix analysis*. The bottom window is the information and instruction window. This window shows the values for. all variables entered by the operator. The maxima present themselves either as a single blue pixel, a black pixel between two blue pixels or a blue pixel between two other blue pixels. It can also be observed that the start and endpoints of the image bear no curvature maxima. The start and end points are, however, candidates for measurement. These points can be added in the editing screen of the software.

Figure 6 displays the editing screen of the *matrix analysis* module. Blue pixels can either be added to the image (for example at the start and end-point) or removed from the image. The operator is required to locate the pixel of interest using the cursor and the PIG routine as has been described (Found, Rogers & Schmittat, 1994). At the end of the editing process the image is in a form where each measurement point is represented by a single blue pixel.

The total number of peaks present in the signature showing all of the required measurement points are

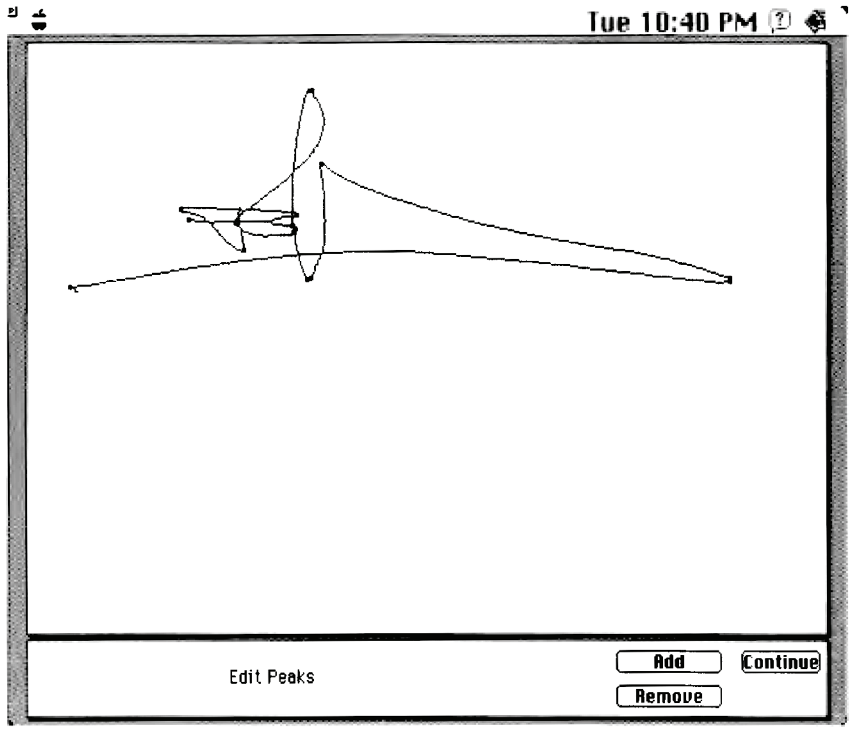


FIGURE 6. The peak editing screen. The operator can interact with the software to add or subtract measurement points on the image.

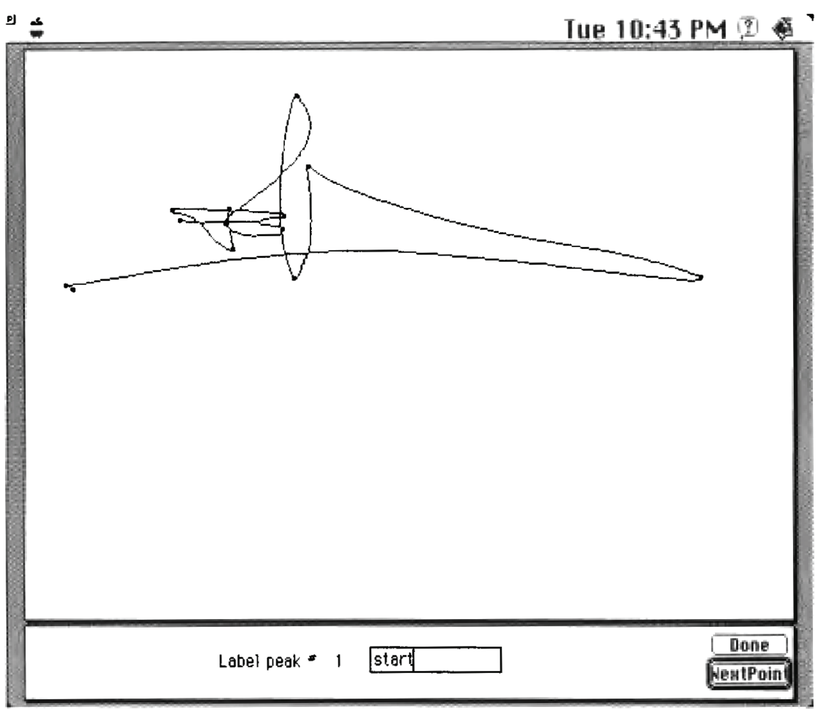


FIGURE 7. The peak labelling screen. The operator can interact with the software to label the measurement points used in the analysis. These labels are used to identify data in the results spreadsheet.

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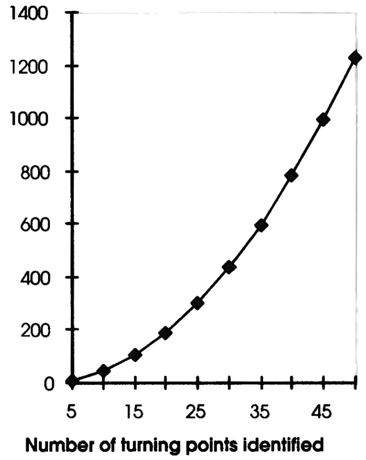

FIGURE 8. A plot of the number of.turning points identified versus the number of raw measurements generated per signature.

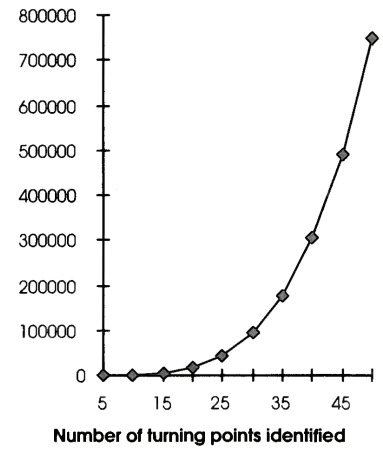

FIGURE 9. A plot of the number of turning points identified versus the number of ratio comparison measurements generated per signature.

now entered into the computer. This value sets the number of rows in the raw results spreadsheet.

The operator is now required to number each of the peaks in order of temporal production. Peaks not numbered are automatically deleted from the calculation. Once this process is completed the operator can enter descriptive labels for each of the peak numbers to assist in the identification of the points measured from the results spreadsheets (Figure 7).

The program now stores the coordinates for the turning point pixels associated with the image analysed, along with the calibration data. The next signature can then be analysed in the same manner (excluding the need to enter labels as the relationship between peak number and descriptive label is now set). At the end of the standard image group the number of questioned images is entered. The same process is conducted on the questioned signature group. When all of the questioned signatures have been analysed, the operator is given the facility to calculate the comparison results in two ways: raw results and ratio results.

8. Raw Results

Raw results are a calculation of the mean, minimum value, maximum value and standard deviation of the data for each of the distances between each of the measurement points for the standard image group. Each of the values for the corresponding data point for each of the questioned images is then calculated and compared to the minimum and maximum value of this point in the standard group. Results of this comparison are flagged as either inside or outside the range of variation on the spreadsheet using a tick or cross symbol. A total of the number of questioned values falling in the range or outside the range of the standard image group is presented at the base of the results spreadsheet. The percentages calculated from these values is the % spatial consistency score. Participant data points contributing to this final score can be derived by visual inspection of the results in the spreadsheet in combination with the labels. Figure 8 provides a plot of the number of turning points identified versus the number of raw measurements generated per signature.

9. Ratio Results

The ratio results subroutine recalculates from the raw data files all combinations of ratios between data points. This provides a total spatial consistency score in the same way as has been discussed in the previous section. Figure 9 provides a plot of the number of turning points identified versus the number of ratio comparison measurements generated per signature.

10. Discussion

The controversy surrounding the relationship between Document Examination and science has been reported (Risinger, Denbeaux & Saks, 1989; Huber & Headrick, 1990). This controversy has culminated in a recent pivotal court decision where it was concluded that forensic handwriting examination could not properly be characterized as scientific in nature (United States v. Starzecpyzel, 1995). Although a variety of factors contributed to this decision, methodological shortfalls in both research and casework investigations arising out of the almost total absence of objective comparison techniques can be seen as a major issue for the field. The most relevant work which may be applied to this problem can be found in the signature identification, signature verification and optical character recognition literature. To date, however, there has been no report of a technique that has been directly carried across and applied routinely in the field of forensic document examination. This is not so surprising given that forensic examiners deal with static images and comparison samples which do not necessarily capture the normal range of behaviour of a particular writer. Compounding this problem is the reality that the analysis of space is only one factor in the overall decision making process regarding the authorship of the image. Spatial information is important, however, when examiners make determinations about whether or not a particular image is consistent or inconsistent with a body of standard material. This is carried out not only on the basis of space, but also on line quality. Any opinion settled upon at this stage is not about authorship but rather about formulating an appropriate set of hypotheses such that issues of authorship based on theoretical considerations of image complexity can be investigated (Found & Rogers, 1995; Found & Rogers, 1998). Given this philosophical approach, our software research to date has focused purely on the issue of spatial scoring and not on the issue of predicting writer identity directly from this score. In view of the most recent submission (Found & Rogers, 1998) regarding underlying theoretical considerations associated with forensic handwriting examinations, this would seem the most appropriate starting point for the eventual inclusion of techniques such as those described here.

The philosophy behind the PEAT program was basically to introduce into the field of handwriting comparison research and casework a technique that generates objective spatial comparison data from common static handwriting traces. Early versions of the program provided the tools necessary to take a variety of length, area and angle measurements which offered solutions to the measurement problems associated with non-linear and intersecting handwriting traces. Although these techniques did provide useful data when comparing genuine to simulated questioned images, the overall approach fell short of the ultimate aims of spatial analysis in casework. The primary concerns proved to be in the areas of operator analysis time and ultimate objectivity in measurement point selection and data generation.

The number of features that could be measured from a two dimensional image to generate a spatial consistency score are very large should curved line length, distance between two points, areas and angles be taken into consideration, both independently and in combination. A whole variety of these measurements could be taken, in each of the modules, by the operator. Of critical importance, given the spatial measurement strategy, was what should be measured and, given the time intensive nature of the task, what the operator neglected to measure. Given this shortfall, similar criticisms could be made of the technique, with regards to its subjectivity, as can be levelled at existing visual comparison methodologies.

The angular differential software provides a method to at least in part compensate for this potential source of criticism. This module could be used in two ways: either to directly identify turning points from which the operator could manually take distance between two point measurements using the appropriate PEAT module, or to validate measurement points identified by the operator's eye. This module, however, did not provide a fast method to edit the points, or to actually measure the distances between the points. In addition, even though the act of measuring between the points was simple, within the distance between two points module alone, if the number of points that were chosen to be measured was large, the process would become extremely time-consuming and open up opportunity for operator errors. Given an image exhibiting 10 turning points (which for a typical signature is low), the operator would in each instance need to identify, using the PIG grid, the two relevant data points for each of the ten measures. Up to the point where the *matrix analysis* technique was developed the emphasis remained, to a certain extent, on the ability of the operator to choose what actual measurements would be made. Although this process can be criticised, it is still an improvement on the traditional technique of visual inspection and estimation that have been, and are, used.

The most important feature of the *Matrix Analysis* technique is that the spatial score that is produced combines every possible combination of straight line measurements from the data points. There can, therefore, be no criticism that relevant measurements have been excluded. In addition, the technique is very fast. Once the measurement points have been selected and numbered, the actual calculation of the measurements is performed automatically.

11. Future Directions

The future for techniques of this type can be thought of in terms of speed and the relationship between spatial analysis, line quality analysis and issues regarding authorship. Analysis time, although not a fundamental concern in research of this type, may ultimately impact on whether techniques such as those described here will be introduced into routine casework. There is clearly a significant time difference between looking at an image and making a spatial consistency judgement, and analysing the image objectively and making a judgement. Time savings could be made at a number of levels in the analysis process. The following suggestions are but a few.

12. Scanning

The scanning and photocopying enlargement process can very easily be replaced using a CCD camera linked directly to the computer. Images appearing on documents can then be directly stored in a digital form along with the calibration grid. These images can be scaled simply by altering the zoom on the camera.

13. *Curvature Maxima Selection*

Studies could be undertaken to determine whether handwriting experts are able to accurately and repeatedly pick the points of maximum curvature by eye. This study would involve determining the relationship between the curvature maxima identified by the operator within the *matrix analysis* peak edit section, with those curvature maxima selected by the angular differential program. A correlation could be calculated to illustrate the strength of the relationship between these variables.

14. Manual Systems

Given the success of the above proposed experiment, the need to actually enter the entire image into the computer and process that image could theoretically be avoided. A digitising pad and associated pen could be connected to the *matrix analysis* program. The pad would be calibrated. The document or a copy bearing the image of interest could be placed on the pad. The operator would identify the curvature maxima by placing the pen on the turning point and providing a signal through the attached switch. The program would perform the normal analysis functions on the array of turning points provided from each image. We estimate that this would decrease the analysis time by up to 80%. We stress, however, that it moves back from the entirely objective approach as has been described. Ultimately, compromise of this type may be the only way to elicit change in the short term.

Ultimately we are moving towards systems which would employ technology such as neural networks to predict whether questioned signatures are genuine or simulated. Data generated from software such as the *matrix analysis* technique, from complexity models such as that reported by Found and Rogers (1995), and from either a validated subjective line quality scoring technique, or a yet to be reported objective method, would be put into such a network, along with the identity of the questioned signature. Variations in the amount and date range of questioned and standard material could also be introduced. Such a technique could then be subjected to validation trials and the error rate calculated. This type of objectivity in forensic science forms the future goal for research of this type and offers considerable promise to the field of forensic handwriting examination. The timeliness of the availability of such systems is almost exclusively dependent on the enthusiasm of researchers in the forensic, signature verification, signature identification, optical character recognition and behavioural science fields, in combination with the participation of financial supporters to fund the required research.

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